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Modelling green macroalgal blooms on the coasts of Brittany, France to enhance water quality management

Thierry Perrot [a,*], Nadège Rossi [a], Alain Ménesguen [b], Franck Dumas [b]

[a] Centre d'Etude et de Valorisation des Algues (CEVA), Presqu'île de Pen Lan BP3, 22610 Pleubian, France
[b] Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), BP 70, 20280 Plouzané, France

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ABSTRACT

First recorded in the 1970s, massive green macroalgal blooms have since become an annual recurrence in Brittany, France. Eutrophication (in particular to anthropogenic nitrogen input) has been identified as the main factor controlling *Ulva* 'green tide' events. In this study, we modelled *Ulva* proliferation using a two-dimensional model by coupling hydrodynamic and biological models (coined 'MARS-Ulves') for five sites along the Brittany coastline (La Fresnaye Bay, Saint-Brieuc Bay, Lannion Bay, Guissény Bay and Douarnenez Bay). Calibration of the biological model was mainly based on the seasonal variation of the maximum nitrogen uptake rate (V_{maxN}) and the half-saturation constant for nitrogen (K_N) to reproduce the internal nutrient quotas measured *in situ* for each site. In each bay, model predictions were in agreement with observed algal coverage converted into biomass. A numerical tracking method was implemented to identify the contribution of the rivers that empty into the study bays, and scenarios of decreases in nitrate concentration in rivers were simulated. Results from numerical nitrogen tracking highlighted the main nitrogen sources of green tides and also showed that each river contributes locally to green tides. In addition, dynamic modelling showed that the nitrate concentrations in rivers must be limited to between 5 and 15 mg l^{-1}, depending on the bay, to reduce *Ulva* biomass by half on the coasts. The three-step methodology developed in this study (analysing total dissolved inorganic nitrogen flux from rivers, tracking nitrogen sources in *Ulva* and developing scenarios for reducing nitrogen) provides qualitative and quantitative guidelines for stakeholders to define specific nitrogen reduction targets for better environmental management of water quality.

1. Introduction

Massive development of opportunistic green macroalgae is a worldwide phenomenon related to coastal water eutrophication (Valiela et al., 1997). In coastal environments, there are different types of green tides. Green tides can occur on mud flats—as reported in Italy (Viaroli et al., 2005), Spain (Hernandez et al., 1997), Denmark (Lyngby et al., 1999; Pedersen and Borum, 1996; Riisgard et al., 2008), the Netherlands (Malta and Verschuure, 1997), the USA (Nelson et al., 2008), Ireland (Jeffrey et al., 1995) and the UK (Scanlan et al., 2007)—or on sandy beaches where free floating macroalgae wash up on beaches—as in France (Merceron et al., 2007; Piriou et al., 1991) and in China (Liu et al., 2010). The main consequences of macroalgal blooms include oxygen depletion in calm waters, which causes changes in the zoobenthic community (Norkko and Bonsdorff, 1996), decline in seagrass populations (McGlathery, 2001), and production of hydrogen sulphide (Briand, 1989). In all cases, nutrient enrichment due to anthropogenic activity is the main cause of these macroalgal blooms. Opportunistic macroalgae are therefore one of the quality indicators listed in the European Water Framework Directive (WFD, 2000). Although eutrophication occurs in all aquatic ecosystems, coastal waters are particularly sensitive because they represent the last compartment where all nutrient inputs accumulate from the entire water cycle and run-off waters. For this reason, marine estuaries have the highest nutrient inputs per unit surface area of all aquatic ecosystems (Howarth, 1993). For instance, in Brittany, in 2008, almost 76,000 t of nitrogen was discharged into the sea according to the Loire-Brittany Water Agency. Brittany has the highest positive nitrogen balance in France due to intensive farming activities (Campling et al., 2005). Nutrient enrichment, combined with semi-enclosed areas with poor flushing, shallow depths and particularly clear waters, has made Brittany coasts very sensitive to macroalgal blooms, which are generally composed of drifting *Ulva* spp. (Dion and Le Bozec, 1996). Macroalgal 'green tides' have been a regular occurrence in Brittany since the 1970s (Merceron et al., 2007; Piriou et al., 1991) in both coastal and transitional waters and have become a real environmental issue. Since 2002, green macroalgae blooms occurring on Brittany coasts have been monitored (CEVA, 2011). Washed-up and drifting green algae covered almost 1000 ha of sandy beaches or bays in Brittany in June 2009. To avoid negative impacts on tourism and risks for human health related to decomposition gases, green algae are now being collected on numerous beaches. In 2010, nearly 74,000 m^3 of green algae were collected in Brittany (CEVA, 2011). However, removal and disposal of seaweeds are only short-term solutions.

* Corresponding author. Tel.: +33 2 96 22 93 50; fax: +33 2 96 22 84 38.
E-mail address: thierry.perrot@ceva.fr (T. Perrot).

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These actions must be accompanied by preventive measures, such as upstream reduction in nitrate inputs in aquatic ecosystems. Numerous models have been constructed to determine which factors control macroalgal blooms (Brush and Nixon, 2010; Ménesguen and Salomon, 1988; Runca et al., 1996; Solidoro et al., 1997). For management purposes, these models mainly provide qualitative recommendations and sometimes quantitative guidelines. In Brittany, it is now known that macroalgal blooms occurring in coastal waters are principally due to anthropogenic nitrogen loading (Ménesguen and Piriou, 1995; Piriou and Ménesguen, 1990). Due to the high cost of the preventive actions, catchment area managers need highly reliable prediction tools to set nitrate concentration targets for the main rivers and thus control green tides. However, there are no models to accurately estimate the effects of nitrate load reduction on green tides with regard to water management issues. The MARS-Ulves model is derived from two coupled models: a two-dimensional (2D) version of the hydrodynamic model MARS (Lazure and Dumas, 2008), and an improved version of the biogeochemical model of *Ulva* production described by Ménesguen et al.

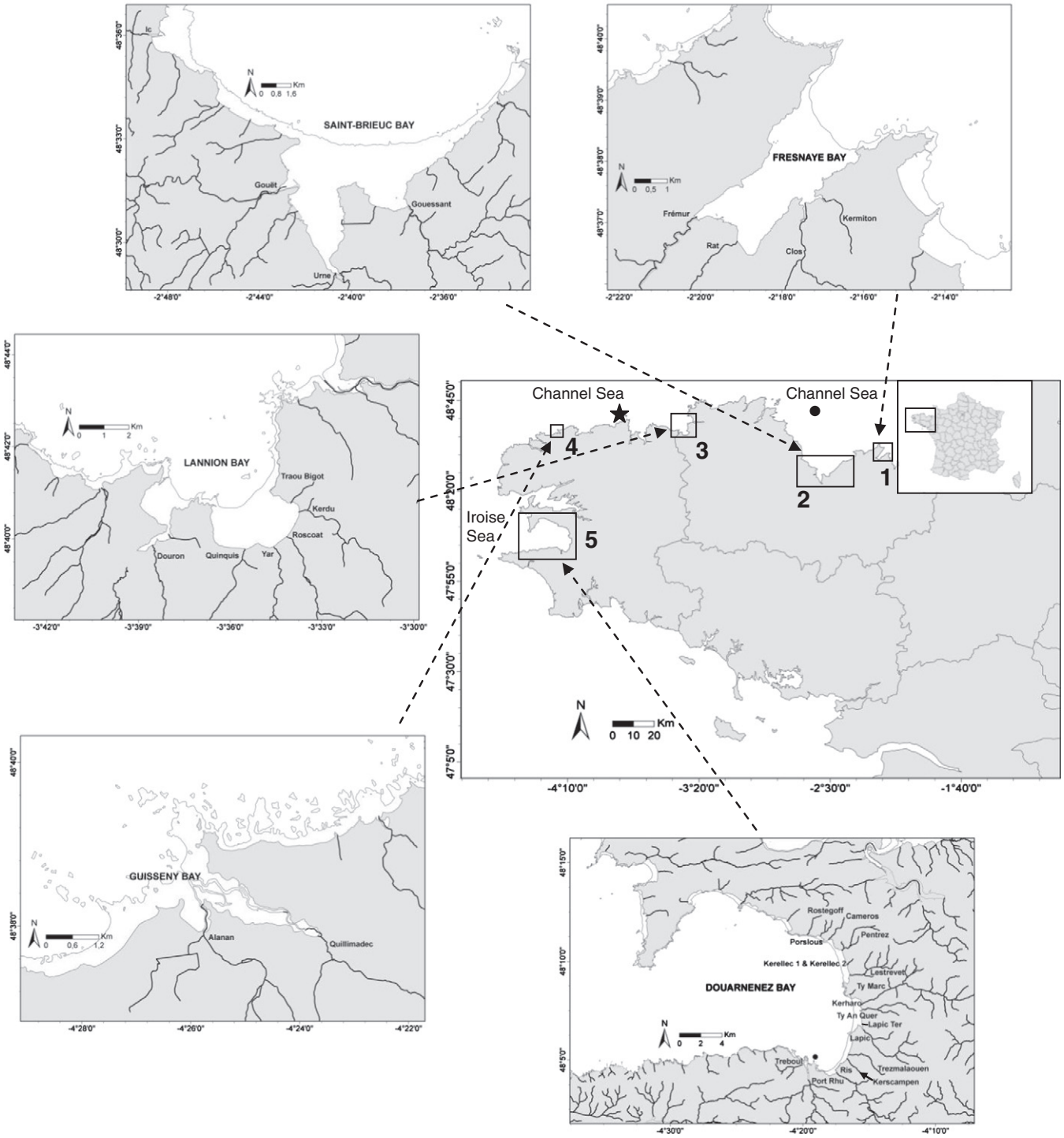

Fig. 1. Map of Brittany. Arrows indicate the bays that were modelled. 1—La Fresnaye Bay, 2—Saint-Brieuc Bay, 3—Lannion Bay, 4—Guissény Bay, 5—Douarnenez Bay (the black dot • indicates where water from the sewage treatment plant is discharged into the sea (at a depth of 10 m). The black star indicates the location of the Estacade site and the black circle the location of the extraction of the generic offshore time-series for NO_3, NH_4 and PO_4.